Resonant photon tunneling enhancement of the van der Waals friction

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Abstract

We study the van der Waals friction between two flat metal surfaces in relative motion. For good conductors we find that normal relative motion gives a much larger friction than for parallel relative motion. The friction may increase by many order of magnitude when the surfaces are covered by adsorbates, or can support low-frequency surface plasmons. In this case the friction is determined by resonant photon tunneling between adsorbate vibrational modes, or surface plasmon modes.

A great deal of attention has been devoted to non-contact friction between nanostructures, including, for example, the frictional drag force between two-dimensional quantum wells [1, 2, 3] , and the friction force between an atomic force microscope tip and a substrate [4, 5, 6, 7, 8].

In non-contact friction the bodies are separated by a potential barrier thick enough to prevent electrons or other particles with a finite rest mass from tunneling across it, but allowing interaction via the long-range electromagnetic field, which is always present in the gap between bodies. The presence of inhomogeneous tip-sample electric fields is difficult to avoid, even

under the best experimental conditions [6]. For example, even if both the tip and the sample were metallic single crystals, the tip would still have corners present and more than one crystallographic plane exposed. The presence of atomic steps, adsorbates, and other defects will also contribute to the inhomogeneous electric field. The electric field can be easily changed by applying a voltage between the tip and the sample.

The electromagnetic field can also be created by the fluctuating current density, due to thermal and quantum fluctuations inside the solids. This fluctuating electromagnetic field is always present close to the surface of any body, and consist partly of traveling waves and partly of evanescent waves which decay exponentially with the distance away from the surface of the body. The fluctuating electromagnetic field originating from the fluctuating current density inside the bodies gives rise to the well-known long-range attractive van der Waals interaction between two bodies [9]. If the bodies are in relative motion, the same fluctuating electromagnetic field will give rise to a friction which is frequently named as the van der Waals friction.

Although the dissipation of energy connected with the non-contact friction always is of electromagnetic origin, the detailed mechanism is not totally clear, since there are several different mechanisms of energy dissipation connected with the electromagnetic interaction between bodies. First, the electromagnetic field from one body will penetrate into the other body, and induce an electric current. In this case friction is due to Ohmic losses inside the bodies. Another contribution to friction from the electromagnetic field is associated with the time-dependent stress acting on the surface of the bodies. This stress can excite acoustic waves, or induce time-dependent deformations which may result in a temperature gradient. It can also induce motion of defects either in the bulk, or on the surface of the bodies. The contribution to friction due to nonadiabatic heat flow, or motion of defects, is usually denoted as internal friction.

It is very worthwhile to get a better understanding of different mechanisms of non-contact friction because of it practical importance for ultrasensitive force detection experiments. This is because the ability to detect small forces is inextricably linked to friction via the fluctuation-dissipation theorem. For example, the detection of single spins by magnetic resonance force microscopy, which has been proposed for three-dimensional atomic imaging [14] and quantum computation [15], will require force fluctuations to be reduced to unprecedented levels. In addition, the search for quantum gravitation effects at short length scale [16] and future measurements of the

dynamical Casimir forces [17] may eventually be limited by non-contact friction effects.

Recently Gotsmann and Fuchs [5] observed long-range non-contact friction between an aluminum tip and a gold (111) surface. The friction force F acting on the tip is proportional to the velocity v, $F = \Gamma v$. For motion of the tip normal to the surface the friction coefficient $\Gamma(d) = b \cdot d^{-3}$, where d is the tip-sample spacing and $b = (8.0^{+5.5}_{-4.5}) \times 10^{-35} \mathrm{N\,s\,m^2}$ [5]. Later Stipe *et.al.*[6] observed non-contact friction effect between a gold surface and a gold-coated cantilever as a function of tip-sample spacing d, temperature T, and bias voltage V. For vibration of the tip parallel to the surface they found $\Gamma(d) = \alpha(T)(V^2 + V_0^2)/d^n$, where $n = 1.3 \pm 0.2$, and $V_0 \sim 0.2\,\mathrm{V}$. At 295K, for the spacing $d = 100$Å they found $\Gamma = 1.5 \times 10^{-13}\,\mathrm{kgs^{-1}}$, which is ∼500 times smaller that reported in Ref. [5] at the same distance using a parallel cantilever configuration.

In a recent Letter, Dorofeev *et.al.* [4] claim that a the non-contact friction effect observed in [4, 5] is due to Ohmic losses mediated by the fluctuating electromagnetic field . This result is controversial, however, since the van der Waals friction has been shown [10, 11, 12, 13] to be many orders of magnitude smaller than the friction observed by Dorofeev *et.al.* Presently, the origin of the difference in magnitude and distance dependence of the long-range non-contact friction effect observed in [5] and [6] is not well understood.

In order to improve the basic understanding of non-contact friction, in this Letter we present new results for van der Waals friction. In [11] we developed a theory of van der Waals friction for surfaces in parallel relative motion. Here we generalize the theory to include also the case when the surfaces are in normal relative motion, and we show that there is drastic difference between these two cases. Thus, for normal relative motion of clean good conductor surfaces, the friction is many orders of magnitude larger than for parallel relative motion, but still smaller than observed experimentally. Another enhancement mechanism of the non-contact friction can be connected with resonant photon tunneling between states localized on the different surfaces. Recently it was discovered that resonant photon tunneling between surface plasmon modes give rise to extraordinary enhancement of the optical transmission through sub-wavelength hole arrays [18]. The same surface modes enhancement can be expected for van der Waals friction if the frequency of these modes is sufficiently low to be excited by thermal radiation. At room temperature only the modes with frequencies below $\sim 10^{13} s^{-1}$ can be excited. For normal metals surface plasmons have much too high

frequencies; at thermal frequencies the dielectric function of normal metals becomes nearly purely imaginary, which exclude surface plasmon enhancement of the van der Waals friction for good conductors. However surface plasmons for semiconductors are characterized by much smaller frequencies and damping constants, and they can give an important contribution to van der Waals friction. Other surface modes which can be excited by thermal radiation are adsorbate vibrational modes. Especially for parallel vibrations these modes may have very low frequencies.

Recently [10] we developed a theory of the van der Waals friction between two-semiinfinite bodies, moving parallel to each other. We have generalized this theory to two-semiinfinite bodies, moving normal to each other. The frictional stress, σ, is proportional to the velocity v, $\sigma = \gamma v$.

For the separation $d < c\hbar/k_BT$ we get coefficient of friction $\gamma_\perp$ [23]:

$$\gamma_\perp = \frac{\hbar}{\pi^2}\int_0^\infty d\omega \int dq q^3 \left(-\frac{\partial n(\omega)}{\partial \omega}\right) e^{-2qd}$$
$$\times \Big\{((\mathrm{Im}R_{1p} + e^{-2qd}\,|R_{1p}|^2\,\mathrm{Im}R_{2p})(\mathrm{Im}R_{2p} + e^{-2qd}\,|R_{2p}|^2\,\mathrm{Im}R_{1p})$$
$$+e^{-2qd}(\mathrm{Im}(R_{1p}R_{2p}))^2)\frac{1}{|1-e^{-2qd}R_{1p}R_{2p}|^4} + [p \to s]\Big\} \qquad (1)$$

where the Bose-Einstein factor

$$n(\omega) = \frac{1}{e^{\hbar\omega/k_BT} - 1} \qquad (2)$$

The symbol $[p \to s]$ in (1) denotes the term which is obtained from the first one by replacement of the reflection factor $R_p(\omega)$ for $p-$ polarized waves by the reflection factors $R_s(\omega)$ for $s-$ polarized waves. There is a principal difference between the friction coefficient for normal and parallel relative motion, related to the denominator in (1). The resonant condition corresponds to the case when the denominator of the integrand in (1), which is due to multiple scattering of evanescent electromagnetic waves from opposite surfaces, is small. For two identical surfaces and $R_i << 1 \leq R_r$, where R_i and R_r are the imaginary and real part, respectively, this corresponds to the resonant condition $R_r^2 \mathrm{exp}(-2\mathrm{qd}) \approx 1$. At resonance the integrand in (1) has a large factor $\sim 1/R_i^2$, in sharp contrast to the case of parallel relative motion, where there is no such enhancement factor. The resonance condition can be fullfiled even for the case when $\mathrm{exp}(-2\mathrm{qd}) << 1$ because for evanescent

electromagnetic waves there is no restriction on the magnitude of real part or the modulus of R. This open up the possibility of resonant denominators for $R_r^2 >> 1$.

The reflection factor R_p, which take into account the contribution from an adsorbate layer, is given by [20]:

$$R_p = \frac{q - s/\epsilon + 4\pi n_a q[s\alpha_\parallel/\epsilon + q\alpha_\perp]}{q + s/\epsilon + 4\pi n_a q[s\alpha_\parallel/\epsilon - q\alpha_\perp]}, \tag{3}$$

where

$$s = \sqrt{q^2 - \left(\frac{\omega}{c}\right)^2 \epsilon}, \tag{4}$$

and where $\alpha_\parallel$ and $\alpha_\perp$ are the polarizabilities of adsorbates in a direction parallel and normal to the surface, respectively. ϵ is the bulk dielectric function and n_a is the concentration of adsorbates. For clean surfaces $n_a = 0$, and in this case formula (3) reduces to the well-known Fresnel formula.

Let us first consider two identical metal described by the dielectric function

$$\epsilon = 1 - \frac{\omega_p^2}{\omega(\omega + i\tau^{-1})}, \tag{5}$$

where τ is the relaxation time and ω_p the plasma frequency. For good conductors at thermal frequencies $R_{pi} << 1$ and $R_{pr} \approx 1$. Thus an enhancement in friction is possible only for very small $q << 1/d$. Analysis show that integral (1) has a $1/q^3$-singularity and the main contribution to the integral (1) comes from vicinity of this singularity. For two bodies, moving parallel to each other, the integral has only a logarithmic singularity for small q, and the main contribution comes from the non-resonant region with $q \sim 1/d$. Thus, for clean surfaces of good conductors, for normal relative motion the van der Waals friction will be on many order of magnitude larger than for parallel relative motion. Fig.1 illustrates this situation for two copper surfaces and $T = 273K$. However the van der Waals friction in this case is too small in comparison with experimental data. Thus, for $d = 1nm$ the friction $\gamma_{\perp theor} \sim 10^{-4} kgs^{-1}m^{-2}$. For an atomic force microscope one tip estimate $\Gamma \approx \gamma S$, where $S \approx Rd$ is an effective surface area of the tip with a radius of curvature R. For the tip with $R \sim 1\mu m$ the friction coefficient $\Gamma_{theor} \sim 10^{-19} kgs^{-1}$, while from the experimental data at the same distance one can deduce the friction coefficient $\Gamma_{exp} \sim 10^{-12} kgs^{-1}$ [6].

Resonant photon tunneling enhancement of the van der Waals friction is possible for two semiconductor surfaces which can support low-frequency surface plasmon modes. As an example we consider two clean surfaces of silicon carbide (SiC). The optical properties of this material can be described using an oscillator model [24]

$$\epsilon(\omega) = \epsilon_\infty \left(1 + \frac{\omega_L^2 - \omega_T^2}{\omega_T^2 - \omega^2 - i\Gamma\omega}\right) \tag{6}$$

with $\epsilon_\infty = 6.7$, $\omega_L = 1.8 \cdot 10^{14} s^{-1}$, $\omega_T = 1.49 \cdot 10^{14} s^{-1}$, and $\Gamma = 8.9 \cdot 10^{11} s^{-1}$. The frequency of surface plasmons is determined by condition $\epsilon_r(\omega_p) = -1$ and from (6) we get $\omega_p = 1.78 \cdot 10^{14} s^{-1}$. In Fig.2 we plot the friction coefficient $\gamma(d)$: note that the friction between the two semiconductor surfaces is several order of magnitude larger than between two clean good conductor surfaces.

Another enhancement mechanism is connected with resonant photon tunneling between adsorbate vibrational modes localized on different surfaces. In this case the real part of the reflection factor R_p can be much larger than unity, and the resonant condition $\exp(-2\mathrm{qd})\mathrm{R_p^2} \sim 1$ can be fulfilled even for large q, giving rise to large enhancement of friction. As an example, let us consider ions with charge e^* adsorbed on metal surfaces. The polarizability for ion vibration normal to the surface is given by

$$\alpha_\perp = \frac{e^{*2}}{M(\omega_\perp^2 - \omega^2 - i\omega\eta_\perp)}, \tag{7}$$

where $\omega_\perp$ is the frequency of the normal adsorbate vibration, and $\eta_\perp$ is the damping constant. In Eq. (3) the contribution from parallel vibrations is reduced by the small factor $1/\epsilon$. However, the contribution of parallel vibrations to the van der Waals friction can nevertheless be important due to the indirect interaction of parallel adsorbate vibration with the electric field, via the metal conduction electron [21]. Thus, the small parallel component of the electric field will induce a strong electric current in the metal. The drag force between the electron flow and adsorbates can induce adsorbate vibrations parallel to the surface. This gives the polarizability:

$$\alpha_\parallel = \frac{\epsilon - 1}{n} \frac{e^*}{e} \frac{\omega\eta_\parallel}{(\omega_\parallel^2 - \omega^2 - i\omega\eta_\parallel)} \tag{8}$$

where n is the conduction electron concentration. As an illustration, in Fig.3 we show coefficient of friction for the two Cu(001) surfaces covered by a low

concentration of potassium atoms ($n_a = 10^{18}m^{-2}$) . In the $q-$ integral in Eq.(1) we used the cut off $q_c \sim \pi/a$ (where $a \approx 1nm$ is the inter-adsorbate distance) because our microscopic approach is applicable only when the wave length of the electromagnetic field is larger than double average distance between the adsorbates. In comparison, the friction between two clean surface at separation $d = 1nm$ is seven order of magnitude smaller. At $d = 1nm$ the friction coefficient Γ for an atomic force microscope tip with $R \sim 1\mu m$ is $\sim 10^{-12}kgs^{-1}$ ($\gamma \sim 10^3 kgs^{-1}m^{-2}$, see Fig.2); this is of the same order of magnitude as the observed friction [6].

In this letter, we have shown that the van der Waals friction can be enhanced by several orders of magnitude when the material involved support low-frequency adsorbate vibrational modes or surface plasmon modes. For clean surfaces of good conductors friction is several order of magnitude larger for normal relative motion as compared to parallel relative motion. These results should have broad application in non-contact friction microscopy, and in the design of new tools for studying adsorbate vibrational dynamics.

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FIGURE CAPTIONS

Fig. 1. The friction coefficient for two (clean) surfaces in (a) normal and (b) parallel relative motion, as a function of separation d. $T = 273$K and with parameters chosen to correspond to copper ($\tau^{-1} = 2.5 \cdot 10^{13}s^{-1}$, $\omega_p = 1.6 \cdot 10^{16}s^{-1}$). (The log-function is with basis 10)

Fig.2. The friction coefficient for two clean semiconductor surfaces in (a) normal and (b) parallel relative motion, as a function of the separation d. $T = 300$K and with parameters chosen to correspond to a surfaces of silicon carbide (SiC) (see text for explanation) (The log-function is with basis 10)

Fig. 3. The friction coefficient for two surface covered by adsorbates in (a) normal and (b) parallel relative motion, as a function of the separation d. $T = 273$K and with parameters chosen to correspond to K/Cu(001) [22] ($\omega_\perp = 1.9{\cdot}10^{13}s^{-1}, \omega_\parallel = 4.5{\cdot}10^{12}s^{-1}, \eta_\parallel = 2.8{\cdot}10^{10}s^{-1}, \eta_\perp = 1.6{\cdot}10^{12}s^{-1}, e^* = 0.88e$) (The log-function is with basis 10)

References

[1] T.J. Gramila, J.P. Eisenstein, A.H. Macdonald, L.N. Pfeiffer, and K.W. West, Phys. Rev. Lett. **66**, 1216 (1991); Surf. SCSI. **263,** 446 (1992).

[2] T.J. Gramila, J.P. Eisenstein, A.H. Macdonald, L.N. Pfeiffer, and K.W. West, Phys. Rev. B **47**, 12 957 (1993); Physica B **197,** 442 (1994).

[3] U. Sivan, P.M. Solomon, and H.Shrikman, Phys. Rev. Lett. **68,** 1196 (1992).

[4] I.Dorofeev, H.Fuchs, G.Wenning, and B.Gotsmann, Phys. Rev. Lett. **83,** 2402 (1999).

[5] B.Gotsmann and H.Fuchs, Phys. Rev. Lett. **86,** 2597 (2001).

[6] B.C.Stipe, H.J.Mamin, T.D.Stowe, T.W.Kenny, and D.Rugar, Phys. Rev. Lett. **87,** 096801 (2001).

[7] H.J.Mamin and D.Rugar, Phys. Rev. Appl.Phys. Lett. **79**, 3358 (2001)

[8] P.M.Hoffmann, S.Jeffery, J.B.Pethica, H.Özgür Özer and A.Oral, Phys. Rev. Lett. **87,** 265502 (2001).

[9] I.E.Dzyaloshinskii, E.M.Lifshitz and L.P.Pitaevskii, Adv.Phys., **10**, 165(1961)

[10] A. I. Volokitin and B. N. J. Persson, J.Phys.: Condens. Matter **11**, 345 (1999); *ibid.* Phys.Low-Dim.Struct. **7/8,** 17 (1998).

[11] B.N.J.Persson and A.I.Volokitin, Phys. Rev. Lett. **84**, 3504 (2000).

[12] A.I.Volokitin and B.N.J.Persson, Phys. Rev. B **63**, 205404 (2001); Phys. Low-Dim. Struct. **5/6**, 151 (2001)

[13] A.I.Volokitin and B.N.J.Persson, Phys. Rev. B **65**, 115419 (2002)

[14] J.A.Sidles *et. al.,* Rev. Mod. Phys. **67**, 249 (1995)

[15] G.PBerman, *et. al.,* Phys. Rev. B **61**, 14694 (2000)

[16] N.Arkani-Hamed, S.Dimopoulos, and G.Dvali, Phys. Lett. B **429,** 263 (1998); Sci. Am. **283**, 62 (2000)

[17] U.Mohideen and A.Roy, Phys. Rev. Lett. **81**, 4549 (1998)

[18] A.Krishnan, *et. al.,* Opt.Commun. **200**,1 (2001)

[19] A. I. Volokitin and B. N. J. Persson, J.Phys.: Condens. Matter **13**, 859 (2001)

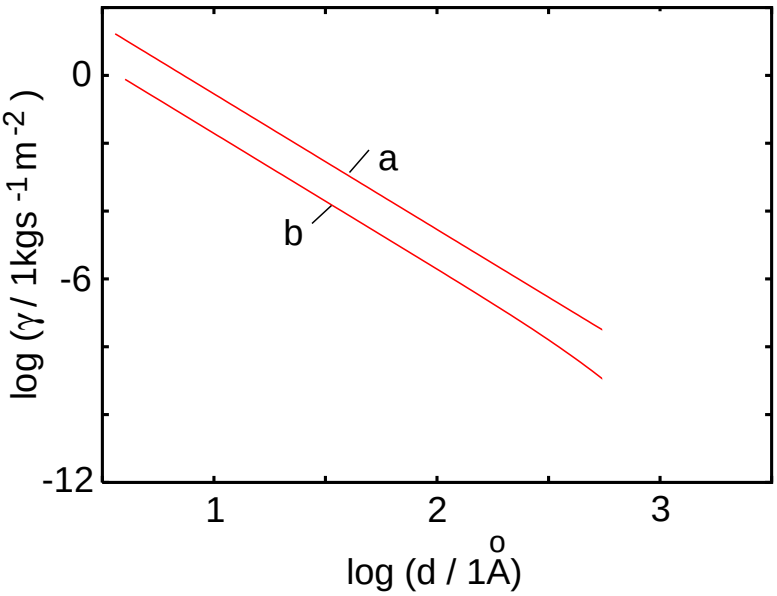
[20] D.C.Langreth, Phys. Rev. B **39,** 10020(1989)

[21] B.N.J.Persson and A.I.Volokitin, Surf. Sci., **310,** 314 (1994)

[22] P.Senet, *et. al.,* Chem.Phys.Lett. **299**,389 (1999)

[23] A. I. Volokitin and B. N. J. Persson, *to be published*

[24] E.D.Palik,*Handbook of Optical Constants of Solids* (Academic, San Diego, CA, 1985)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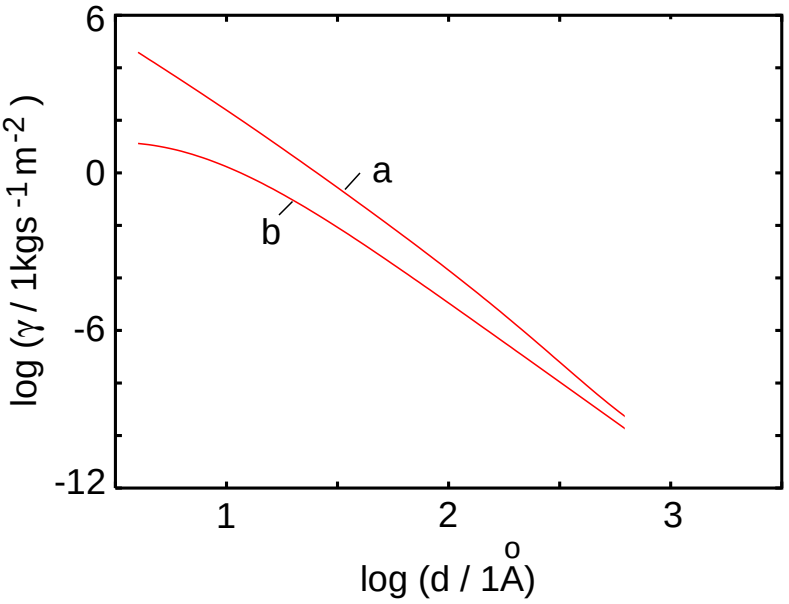
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